

Laser Glass Damage: Computational Analysis of Mitigation Process



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Understanding and controlling the physical processes that cause laser-induced damage to optical components is crucial to the success of many high-energy-density experimental facilities including NIF. Experimental and theoretical investigations of laser damage in silica glass are legion and are actively being pursued within the NIF Program. The insight garnered from experimental data is limited by the extremely short time-scale (~ 1 ns) of the damage events and the complex interplay between energy deposition and hydrodynamic response. A further complication is the stochastic nature of damage initiation, necessitating a *post priori* approach where the damage process must be deduced via forensic reconstruction.

Understanding laser-damage initiation and growth is just half of the problem. Creating an effective strategy to detect and mitigate laser damage is the essential second part. One promising approach is to use infrared wavelength (CO_2) laser energy to excise/anneal the damage site. Key parameters to be optimized include the laser wavelength, intensity, pulse duration, and scan pattern in relation to the size and type of damage site. Both damage initiation/growth studies and mitigation process development could benefit from a high-fidelity

predictive simulation capability that incorporates the essential ingredients of the laser-material interaction and the resulting coupled material response in experimentally relevant configurations.

We are addressing the technical challenges associated with energy deposition, dynamic material response, and the nature of the coupling between these two processes. Our approach is to adapt the current simulations capability within the EMSolve code to simulate the time, space, and material state dependence of the laser energy deposition process. The material's dynamic response is then simulated using advanced multi-phase equations of state (EOS) and failure models within the ALE3D multi-physics code. This also provides some capability to model damage initiation in silica, which would provide a self-consistent facility to establish initial conditions for mitigation studies.

Project Goals

The primary goal is to implement a capability to perform coupled EM simulations of laser energy deposition and subsequent material hydrodynamic response that includes the dependence of the energy deposition processes on local variations in state-dependent material properties.

A key objective is to couple the Hydro and EM simulations to facilitate exploring how strongly this interaction must be implemented. The degree of coupling required to adequately simulate a given phenomenon is problem-dependent and greatly affects the computational costs and efficacy of the overall simulation methodology.

Our technical approach has been as follows.

1. Implement spatial and material state-dependent EM properties, such as the complex dielectric constant. Using a Lorenz-Lorentz formalism, we explicitly modeled the dependence of the material conductivity and permittivity upon density (Fig. 1). This same approach explicitly accounts for the laser energy frequency dependence, thereby facilitating the investigation of this important parameter in candidate mitigation processes. To improve the quality of the boundary conditions of the EM simulations and enhance their dynamic range, we adopted a scattered electric-field methodology (Fig. 2).
2. Adapt existing models of material deformation, phase transformations, and damage to simulate such processes under conditions relevant to laser damage in silica glass. We adopted a unified-creep model for the deformation of silica at high temperatures using material parameters consistent with a linear viscous solid and a temperature-dependent shear modulus. The two-phase EOS is based on combining two analytic forms for the low and high-pressure phases with an irreversible kinetic relation (Fig. 3).
3. As a first step, consider only a single material state variable: the material density. The material density plays a central role in both the hydrodynamic response and the energy deposition.

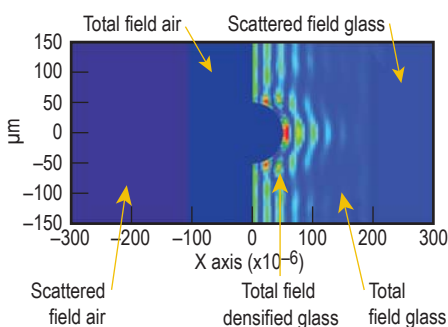


Figure 1. Simulated Joule heating in glass around an artificial defect with 20% greater permittivity and conductivity than the bulk glass.

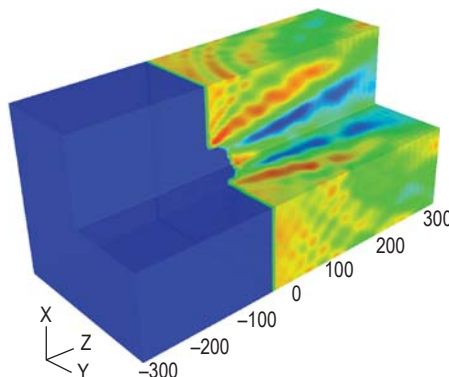


Figure 2. 3-D rendering of laser heat deposition similar to that shown in Fig. 1. Energy deposition varies by a factor of one hundred from blue to red.

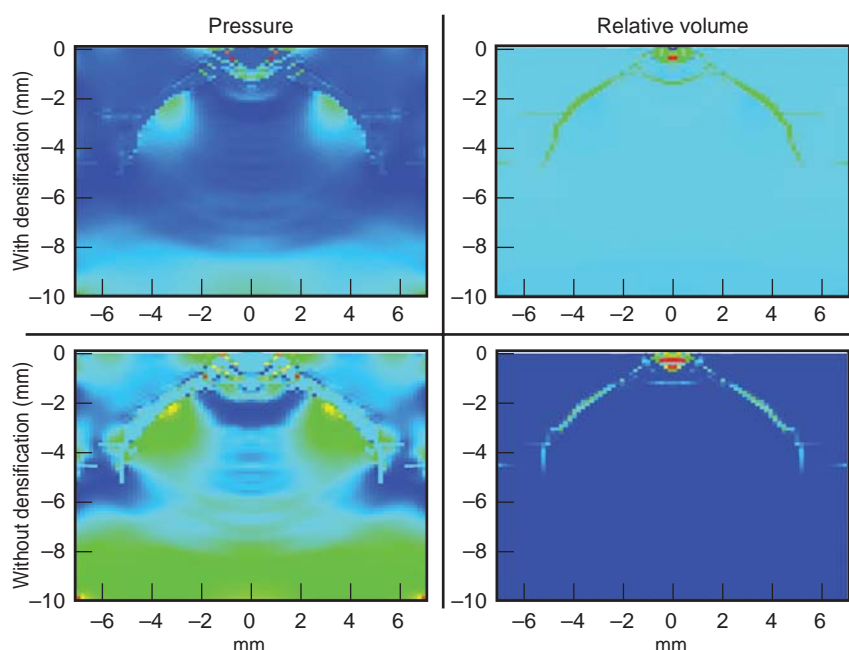


Figure 3. Residual pressure and relative volume following indentation of glass with a smooth circular punch.

Furthermore, under high-pressure loading, such as laser-induced shocks, the reference density of silica is modified, providing material “memory” of previous history such as glass damage.

A loosely coupled scheme was used to connect the hydrodynamics simulations (ALE3D) to the laser energy deposition simulations (EMSolve) via a file passing mechanism (Fig. 4). This approach leverages existing capabilities within ALE3D to specify spatially and temporally varying heat sources using an external file.

Relevance to LLNL Mission

This high fidelity predictive simulation capability, incorporating laser-material interactions and coupled material response, will provide a valuable capability to help advance our understanding of the physical processes involved in optical material damage and mitigation.

FY2007 Accomplishments and Results

A two-phase equation-of-state (EOS) model has been adapted to account for the permanent densification of silica glass that occurs under high-pressure loading. Model parameters have been fit

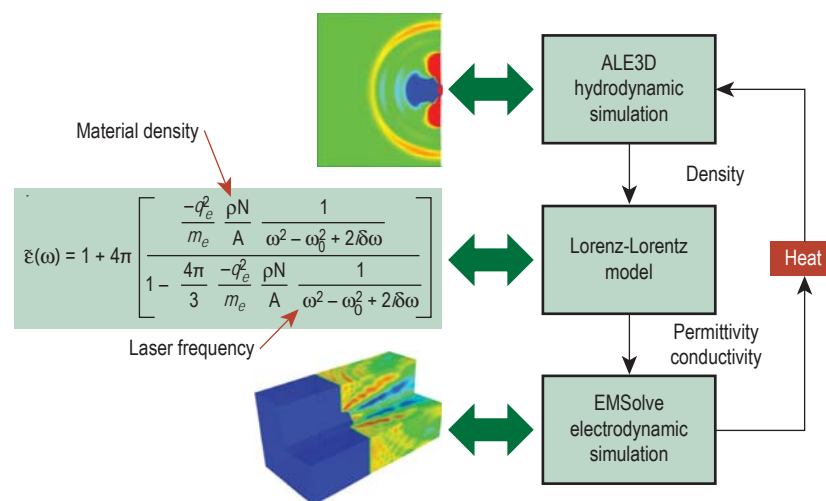


Figure 4. Loosely coupled scheme that includes the effects of laser frequency and material density.

to the reference density, bulk modulus, and thermal expansion coefficients associated with both the high- and low-pressure phases. A simple model of brittle damage has been adapted to account for cracking under tensile loading and successfully tested in conjunction with the above densification EOS model. A scattered electric field formulation has been implemented to improve the efficiency of the E&M simulations.

The capability to account for spatially varying permittivity and conductivity has been implemented. The dependence of the real and imaginary parts of the refractive index on material density and radiation wavelength has been addressed in the framework of a Lorenz-Lorentz model and implemented in the EMSolve code. The Hydro and E&M simulations were coupled via a file-sharing scheme by extending existing capabilities within the ALE3D software and adapting the EMSolve software to import and export the requisite files. An example of a coupled code simulation is shown in Fig. 5.

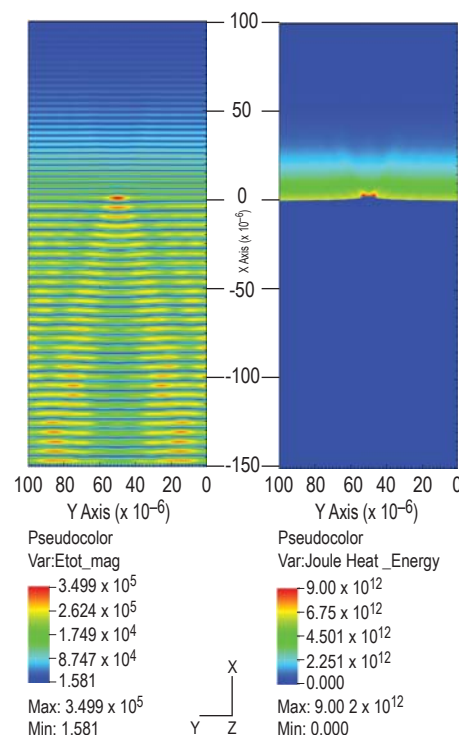


Figure 5. Coupled EMSolve/ALE3D simulation of a laser illuminated damage site similar to that shown in Fig. 3. The total electric field (left) and Joule heating (right) are modulated by local variations in density captured by hydrocode simulation of the indentation process.